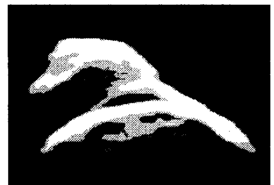
GOLDSTONE RADAR RESEARCH OF NEAR-EARTH ASTEROIDS



NEAR-EARTH ASTEROIDS

STEVEN J. OSTRO

Our planet orbits the Sun amidst a swarm of small asteroids whose existence and importance have been realized only during the past decade. Whereas fewer than 300 of these Earth-orbit-crossing asteroids (ECAs) have been found, so far, the population statistics of objects waiting to be discovered have been established, reliably, from the success rate of optical searches and from analysis of the crater-size distribution of craters in the lunar maria. We are convinced that there are more than 1500 ECAs larger than 1 km, more than 100,000 larger than 100 m, and more than 100,000,000 larger than 10 m. These objects come primarily from the main asteroid belt between Mars and Jupiter, but about 10 percent may be inactive comet nuclei and a few may be pieces of the Moon or Mars. Many ECAs might share (or be) the sources of some of our several thousand meteorites, all of which obviously were ECAs before they fell to Earth. The relationships between ECAs, meteorites, mainbelt asteroids, and comets are central to our understanding of the chemical and dynamical history of the solar system.

The proximity of ECAs presents a double-edged sword of danger and opportunity. Collisions with ECAs constitute a low probability but ultra-high-consequence hazard: there is a 1/1000 chance that human civilization will be threatened by a catastrophic collision during the next century. On the other hand, ECAs also include the cheapest destinations of robotic or piloted space missions. Potential resources such as industrial metals, precious metals, complex organics, chemically bound water and perhaps subsurface ice motivate the exploration of these objects.

Radar is the most powerful ground-based technique for post-discovery investigation of ECAs, for reasons summarized by Table 1. The table illustrates state-of-the-art capability for radar reconnaissance of a fairly large asteroid during a close Earth approach. Radar synthesizes spatial resolution from the distribution of echo power in time delay (range) and Doppler frequency shift (line-of-sight velocity). In principle, it is not hard to resolve a strong target into 10,000 imaging pixels. Moreover, precision of delay-Doppler positional measurements can improve by several orders of magnitude the accuracy of trajectory predictions (e.g., for close Earth approaches or to assist spacecraft navigation).

TABLE 1. FRACTIONAL PRECISION OF ASTEROID RADAR MEASUREMENTS.

	Range (m)	Line-of-Sight Velocity (m/s)
Resolution	~10	0.0001
Asteroid "size"	~1,000	0.01 to 1
Asteroid "location"	~10,000,000,000	10000

Considerable echo strength is needed to be able to take advantage of high-resolution waveforms. Nonetheless, radar reconnaissance of even very weak targets has provided unique information about physical properties. At this writing, radar echoes have been detected from 40 near-earth asteroids. Of those, the Goldstone Solar System Radar (GSSR) has detected 25, and has made the initial detection of 16.

Whereas sensitivity is the primary factor that limits a radar system's capabilities in astrometry or imaging, it is not the only one. The orientational and directional coverage possible with the fully steerable 70-m antenna at Goldstone greatly enhances shape reconstruction and orbit refinement. Similarly, bistatic systems using the 70-m and 34-m antennas have enormous advantages for ECAs that are close, small, or slowly rotating. For all these reasons, the GSSR is, and

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will remain, a unique instrument for ECA reconnaissance. The upgraded Arecibo telescope will have twice the range and will see three times the volume of Goldstone, but Goldstone, which is fully steerable, will see twice the plane-of-sky solid angle, and will cover three times more hour angle than Arecibo, which cannot point more than ~20 degrees from the zenith.

During the past few years, Goldstone observations have achieved a series of breakthroughs in ECA science. In 1992, images of Toutatis (asteroid 4179) achieved the finest absolute spatial resolution of any solar system body by an Earth-based telescope, revealing a cratered, geologically complex object in a slow, nonprincipal-axis rotation state (Figure 1). The rotation is the result of two different types of motion, with periods of 5.4 and 7.3 Earth days that combine in such a way that Toutatis's inertial orientation never repeats. It spins and wobbles like a poorly-thrown football. An explanation for how the asteroid was excited into this spin state is lacking. The 1992 investigations also yielded the ratios of Toutatis's principal moments of inertia; such quantitative information is unavailable for any other asteroid.

Figure 1. High-resolution Goldstone images of Toutatis.

Observations of Geographos (asteroid 1620) in 1994 (Figure 2) yielded a 100-m-resolution movie (available from the author) that shows a 2.5-km by 5-km, paramecium-shaped object. Visible features include several candidate craters, a prominent central indentation, and protuberances at the asteroid's ends that

Figure 2. Outline of Geographos viewed from above its north pole, made by aligning and superposing many frames from the Goldstone radar movie.

may be related to the pattern of ejecta removal and deposition caused by the asteroid's gravity field.

In 1995, observations of Golevka (asteroid 6489; provisionally designated 1991 JX) during its closest approach for at least two centuries included delay-Doppler imaging, two-station (Goldstone-VLA) astrometry, and the first intercontinental planetary radar experiments, from Goldstone to Russia and Japan. Less than 0.6 km across, Golevka is the smallest solar system object imaged so far, and its three-dimensional shape is faceted and angular. Most recently, GSSR images of asteroid 1982 TA showed a ~4-km object with a quasi-triangular equatorial cross section.

The diversity of ECAs is not surprising, given the likelihood that each has suffered a unique, complex history of collisions. Now that realistic physical models of ECAs are being provided by radar, computer simulations can begin to explore the effects of impacts into these bodies as a function of projectile energy, impact location, and target cohesiveness and tensile strength. At present, the

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navigation. Techniques developed in this work area will enable a precision, GPS-based navigation capability for airliners in U.S. airspace by late 1998, greatly improving the safety and operational costs for the public.

"Low Earth Orbiter-Terminal (LEO-T) Development" by Nasser Golshan describes the prototype for a new class of low-cost ground station. The first phase, for downlink only, was completed in 1994 and described in the December 1994 issue of the *DSN Technology Program News*. The second phase, which provides command uplink capabilities, is described in this issue. A week-long demonstration of unattended uplink and telemetry operation of this upgraded configuration with the COsmic Background Explorer (COBE) spacecraft was successfully completed and is reported here.

The DSN Science contribution for this issue is submitted by Steven Ostro, who reports on recent use of the Goldstone Solar System Radar to investigate Earth-crossing asteroids (ECAs). Radar echoes are analyzed to derive precise orbits of newly discovered ECAs and to create thousands of "imaging pixels" that are further processed to produce three-dimensional models and computer-generated images of objects that pass close to the earth. The results suggest that ECAs include unconsolidated rubble piles, single cohesive fragments, and contact binaries. So far, 40 ECAs have been detected. This is expected to increase dramatically during the next few years, as new optical search programs become operational.

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55 percent of NASA's current and planned low-earth orbiter missions; the coverage can be increased to 70 percent by using a 5-m dish instead. In addition to low acquisition cost ($600 K to $800 K for a 3-m system, depending on options), the terminal is highly automated and operates autonomously, resulting in low operations cost. Goddard Space Flight Center is planning to install at least one upgraded LEO-T class ground station with a 5-m antenna at Poker Flats, Alaska to support NASA's polar missions. A new start at JPL, Deep Space Terminal Development, is on a fast track to validate the same cost saving concepts for Deep Space Missions.

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results suggest that ECAs include unconsolidated rubble piles, single cohesive fragments, and a few contact binaries. However, high-resolution radar reconnaissance of a much larger sample of objects is needed. The frequency of ECA radar opportunities is expected to increase dramatically during the next few years, as new optical search programs become operational and more objects are discovered.

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